Monte Carlo radiative transfer in stellar wind

Brankica Šurlan[1,2], Jiří Kubát[1]

[1] Astronomický ústav, Akademie věd České republiky, CZ-251 65 Ondřejov, Czech Republic
[2]Matematički Institut SANU, Kneza Mihaila 36, 11001 Beograd, Serbia

Abstract: Solution of the radiative transfer equation in clumped stellar wind differs significantly from solution in a smooth wind. As a first step necessary to solve this complicated problem we solve the one-dimensional radiative transfer equation using the Monte Carlo method. We present our first preliminary results.

Introduction

In most solutions of the radiative transfer equation in a stellar wind the effect of clumping is taken into account in a parameterized, approximate way using the volume filling factor, which is the ratio of matter density inside clumps and the average matter density, usually accompanied with the assumption of a void interclump medium. Although several attempts have been made to improve this situation, a detailed radiative transfer method that can treat clumping in a more consistent way is still missing. The most promising way for a treatment of radiation transfer in a clumped stellar wind is a Monte Carlo approach. "Classical" solution methods for the radiative transfer equation, like the Feautrier scheme or short characteristics methods, are extremely time and memory consuming when we go to more spatial dimensions than one. This is not the case of Monte Carlo methods, which also allow for simple inclusion of wind inhomogeneities.

As a very first step, we started to develop a code for the formal solution of the radiative transfer equation for given velocity, temperature, and density stratification. We started to develop the code independently from scratch. This task has already been done by many authors for different astrophysical applications, e.g. Abbott & Lucy (1985), Whitney (1991), Lucy & Abbott (1993), de Koter et al. (1997), Vink et al. (1999), Wood et al. (2004), and Kromer & Sim (2009), to name at least some of them. Nevertheless, in order to understand all processes more deeply and to have better control on the code behaviour, we decided to repeat this step.

Wind model

As a toy model we chose the density $\rho(r)$ and velocity $v(r)$ structure from the model of the star with $\mathrm{R}=9.9\,\mathrm{R}_\odot$, $\mathrm{M}=32\,\mathrm{M}_\odot$, and $\mathrm{L}=1.74{\cdot}10^5\,\mathrm{L}_\odot$ ($T_{\mathrm{eff}}=37500\,\mathrm{K}$), having mass loss rate $\dot{\mathrm{M}}=2.8{\cdot}10^{-7}\ \mathrm{M}_\odot$/year and terminal velocity $\mathrm{v}_\infty=3270\,km\ s^{-1}$, which was calculated in Krtička et al. (2009) using a method of Krtička & Kubát (2004). Flux at lower boundary of the wind was computed using the static spherically symmetric NLTE model atmosphere code of Kubát (2003).

Our adopted wind model consists of 90 depth points, which allows us to create 89 zones, similarly to Lucy & Abbott (1993). The values of density ρ are taken to be constant within a zone and equal to the value at the lower radius of the zone. However, the values of the radial velocity $v(r)$ are linearly interpolated inside the zone.

We further introduced several crudely simplifying assumptions. We assumed that all electrons in the wind come from hydrogen ionization, and that hydrogen is fully ionized. The mass of heavier atoms was neglected. Then the electron density, necessary for calculation of the electron scattering opacity, can be simply calculated from the total density by dividing it by a sum of electron and proton masses. The opacity of the medium consists of only two processes, line scattering under Sobolev approximation, and the electron scattering.

Monte Carlo radative transfer

For the solution of the radiative transfer equation we used the Monte Carlo method, basically following the ideas of Lucy (1983) and Abbott & Lucy (1985).

Random number generator As a random number generator used in our Monte Carlo scheme we used a uniform random number generator (Pang, 1997), which generates random numbers in the interval $\langle 0;1)$. Random numbers generated in this way are denoted by ξ, for each application of the random number we generate a new number.

Creation of a photon Frequency of the newly created photons for the Monte Carlo calculations is determined using the emergent flux distribution from the static hydrogen-helium photosphere calculated by a NLTE model atmosphere code (Kubát, 2003), with a help of the acception-rejection method. Then the direction of the photon is randomly chosen with $\cos\theta=\sqrt{\xi}$ and $\phi=2\pi\xi$. Photons are sent from the stellar surface ($R_\star=1$) outwards.

Optical depth calculation After its creation each photon obtains an information how far it is allowed to travel before it undergoes interaction with some particle. It is done by randomly chosen optical depth $\tau_\xi=-\ln\xi$. Then the actual optical depth, which photon passes on its travel, is calculated by summing opacity contribution along its path. This path determines the place of interaction.

We take into account two events which may happen to photon, namely the scattering on free electrons, and resonance line scattering. While the first process acts on all photons with any frequency in the same way, the second process needs that the frequency of a photon meets a Doppler shifted frequency of a scattering atom. If we denote the photon frequency in the observer frame as ν_{obs} and the frequency of the line transition as ν_{line}, then the condition that the line scattering may happen is

$$\nu_{\mathrm{line}}=\nu_{\mathrm{obs}}\left(1-\frac{\boldsymbol{n}\cdot\boldsymbol{v}(r)}{c}\right)$$

where $\boldsymbol{n}$ is a direction of photon propagation and c is the light speed. For radial flow the corresponding optical depth is then

$$\tau_{\mathrm{line}}=\frac{\pi e^2}{m_e c}f_{\mathrm{line}}n_{\mathrm{a}}\left[\mu^2\frac{\mathrm{d}v}{\mathrm{d}r}+\left(1-\mu^2\right)\frac{v}{r}\right]^{-1}$$

where μ is the cosine of the angle between photon propagation direction and the radial direction, n_a is the lower level number density (in our test case arbitrarily taken as $9{\cdot}10^{-9}$ electron density), f_{line} is the line oscillator strength, and m_{e} is the electron mass. The optical depth is evaluated for the radius where line scattering occurs.

The optical depth of the electron scattering τ_{elsc} is calculated as

$$\tau_{\mathrm{elsc}}=n_{\mathrm{e}}(r)\sigma_{\mathrm{e}}$$

for all depths.

If the total optical depth

$$\tau_{\mathrm{line}}+\tau_{\mathrm{elsc}}>\tau_\xi,$$

then photon terminates its travel in the layer where this condition was first fulfilled.

Scattering events After a scattering (either line or electron) photon obtains new direction, chosen randomly for the case of isotropic scattering as $\cos\theta=2\xi-1$ and $\phi=2\pi\xi$ (e.g. Wood et al., 2004). For the case of line scattering, photon obtains a Doppler shifted frequency (in the observer frame)

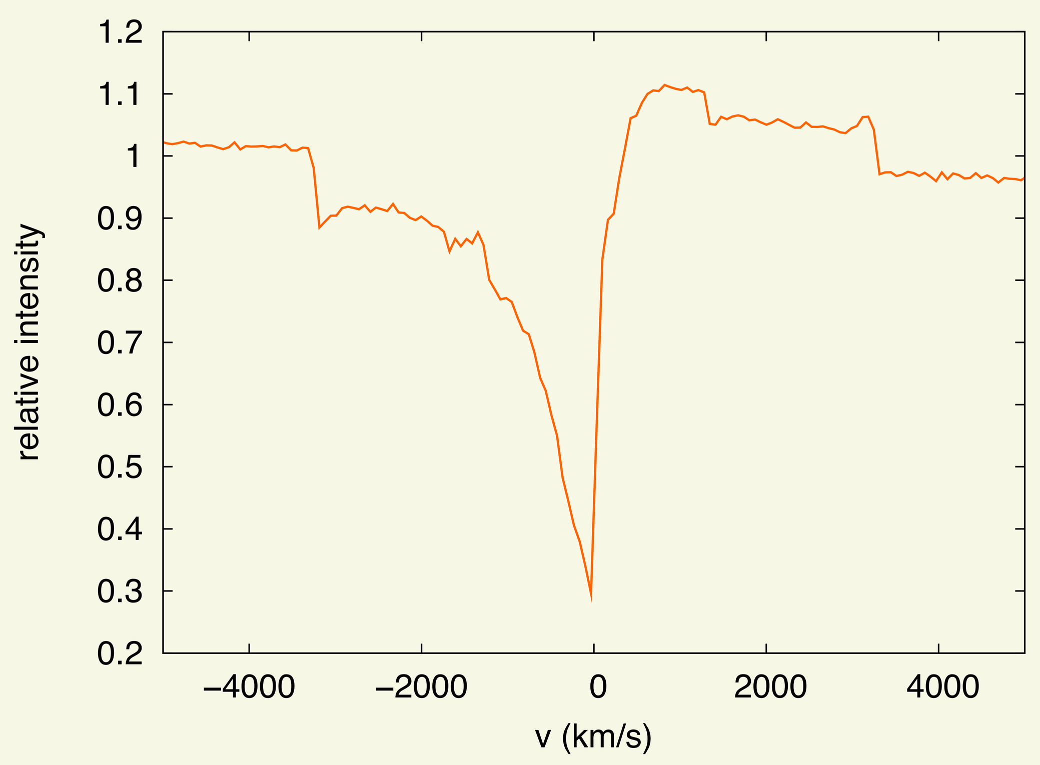
$$\nu_{\mathrm{obs,new}}=\nu_{\mathrm{line}}\left(1-\frac{\boldsymbol{n}\cdot\boldsymbol{v}(r)}{c}\right)^{-1}$$

and a new optical depth τ_ξ may be randomly chosen again.

Binning If the randomly generated optical depth τ_ξ is lower than the total optical depth along the path traveled by the photon, the latter escapes from the wind region either back to the stellar surface or towards the observer. We define a frequency grid, which determines frequency intervals. Each escaping photon is then counted according to its frequency to the proper frequency interval.

Line profile

Here we plot the profile of the line obtained as a result of our calculation. The line has wavelength and oscillator strength corresponding to the hydrogen Hα line. The flux is expressed as relative intensity with respect to local continuum.



The terminal velocity, which follows from the theoretical profile, corresponds well to the terminal velocity of the wind.

In our further work we shall include full line spectrum into our calculations as well as we shall extend the code to 3D to handle inhomogeneous (clumped) stellar wind. Our results will be reported in future papers.

Acknowledgements:

This work has been supported by grants 205/08/0003 and 205/08/H005 (GA ČR). The Astronomical Institute Ondřejov is supported by the project AV0 Z10030501.

References

Abbott, D. C., & Lucy, L. B. 1985, *Astrophys. J.* **288**, 679
de Koter, A., Heap, S. R., & Hubeny, I. 1997, *Astrophys. J.* **477**, 792
Kromer, M., & Sim, S. A. 2009, *Mon. Not. Roy. Astron. Soc.* , in press
Krtička, J., & Kubát, J. 2004, *Astron. Astrophys.* **417**, 1003
Krtička, J., Feldmeier, A., Oskinova, L. M., Kubát, J., Hamann, W.-R. 2009, *Astron. Astrophys.*, submitted
Kubát, J. 2003, in Modelling of Stellar Atmospheres, IAU Symp. 210, N. E. Piskunov, W. W. Weiss & D. F. Gray eds., Astron. Soc. Pacific, B6
Lucy, L. B. 1983, *Astrophys. J.* **274**, 372
Lucy, L. B., & Abbott, D. C. 1993, *Astrophys. J.* **405**, 738
Mazzali, P. A., & Lucy, L. B. 1993, *Astron. Astrophys.* **279**, 447
Pang, T. 1997, An Introduction to Computational Physics, Cambridge Univ. Press
Whitney, B. R. 1991, *Astrophys. J. Suppl. Ser.* **75**, 1293
Wood, K., Mathis, J. S., & Ercolano, B. 2004, *Mon. Not. Roy. Astron. Soc.* **348**, 1337
Vink, J., de Koter, A., & Lamers, H. J. G. L. M. 1999, *Astron. Astrophys.* **350**, 181

Poster presented at the XXVIIth General Assembly of the IAU, Joint Discussion 13, *"Eta Carinae in the Context of the Most Massive Stars"* Rio de Janeiro, Brazil, 13 – 14 August 2009